A HF Tactical Decision Aid for Conventional and Automated Radio Control Systems.

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Introduction

Beyond line of sight (BLOS) communications systems, operating within the high frequency (HF) range (2-30 MHz), propagate electromagnetic waves via the ionisation present in the upper atmosphere (i.e. the ionosphere). The ionosphere, usually considered to lie between heights of -60 and 1000 km, varies in structure over the earth's surface. The vertical ionisation concentration (which historically has been divided into three regions, D, E and F) varies over orders of magnitude and depends on time of day, season, and sunspot number. From a HF communications aspect, the E and F regions essentially act as reflectors whilst the D region acts as an attenuator.

To exploit the time and spatially varying ionosphere for high 'quality' and high 'reliability' HF communications links, the HF system signal power, operating frequency, antenna, modulation, and data-rate etc., should be matched to the prevailing ionospheric conditions. Some manual matching is currently performed by HF operators using daily frequency schedules based on the maximum usable frequencies (MUF). These frequencies can be anticipated using HF prediction programs such as REC533A [*CCIR,* 1994] and IONCAP [*Teters et al.*, 1983]. Alternatively the frequencies maybe measured in near real-time using oblique chirp ionosondes [*Barry* et *al.*, 1969, *Arthur et al., 1994],* or simply estimated based on HF operators experience and expertise.

The communications matching process currently performed is limited, time intensive and often requires an experienced HF operator. Frequently it results in the selection of sub-optimal system configurations (e.g. incorrect frequency, insufficient transmitter power). To overcome these drawbacks automatic link establishment (ALE) systems have been developed. The next generation of HF communications system may incorporate an improved version of ALE known as Automated Radio Control Systems (ARCS *Arthur and Maundrell, 1994).* ARCS will match a number of system parameters (e.g. data rate, modulation, optimum receiver station as well as frequency and power) and requirements to the prevailing measured ionospheric conditions. Both manual and automated matching techniques, however, are primarily concerned with maximizing link 'reliability' and 'quality'. Little attention is given to the Electronic Protective Measures (EPM) required to minimise the jamming, interception and direction finding vulnerability of the communications link about to be established.

EPM procedures employed by HF systems are currently based on techniques, such as spread spectrum, cryptography, and antenna nulling. Unfortunately, these techniques, may still propagate electromagnetic energy to unwanted or unauthorised receivers causing interference or resulting in the transmission of intelligence. There is, however, an alternative technique. This technique is based on the tactical use of signal propagation [*Argo and Rothmuller, 1979, Goodman et al.,* 1982, *Shukla and Cannon,* . . *1992]* and exploits detailed knowledge of the ionosphere and ray-tracing techniques to minimise the signal coverage and thereby deny unauthorised access to the radiated electromagnetic energy. The technique could be used either in isolation or in conjunction with other EPM approaches such as antenna nulling and spread spectrum techniques.

This paper describes the tactical propagation technique via the development of an HF decision aid. This decision aid uses an ionospheric environmental model in conjunction with a communications model to predict both the interception and jamming vulnerability of required HF links. Based on the model outputs, the decision aid recommends system configurations (e.g. best frequency, best ground station, best transmission time) which minimise system vulnerability. The tactical decision aid can be used by HF operators in near real-time, as an additional component in other electromagnetic modelling systems (e.g.

EEMS [*Moore and Lewis*, 1994]) or, off-line during mission planning to predict and configure the least vulnerable HF communications links. The decision aid could also be used to automatically configure current HF equipment. This latter approach is particularly powerful when used in conjunction with ARCS [*Arthur and Maundrell 1994*] based systems with the decision aid contributing to the automatic channel selection (ACS) process.

This paper first outlines the general concepts of an HF decision-aid. A decision-aid currently being developed at the Defence Research Agency, the utility of which is also described by *Moore and Shukla [1996]* will then be described. The paper shows how the decision aid uses simple frequency management techniques to minimise signal interception and will outline the future development of the decision-aid.

Principle elements of a HF communications decision aid systems

A decision aid system designed to optimise EPM communications characteristics should ideally comprise three principle elements (Figure 1): an information gathering and distribution system, a jamming and interception model (JIM), and a communications equipment interface. The first element should provide the second element (JIM) with as much near real-time data as possible. This data may consist of wanted (i.e. friendly) and unauthorised or unwanted (i.e. hostile) receiver locations, hostile capabilities, ionospheric data from sounders, sunspot number, time, date, etc.

The final element, the communications equipment interface, should ensure that the recommended system configurations are presented to the operator and used by the communications system in the most effective manner. The information gathering and distribution system and, the communications interface are not detailed any further at this stage suffice to say that some of the main elements can be found within ARCS [*Arthur and Maundrell, 1994*].

The jamming and interception element should ideally comprise of six primary models (Figure 1): an input / update interface, a propagation prediction model, an ionospheric model, a communications model, a vulnerability assessment model and, a systems recommendations model. The following details an idealised design of a JIM and some implementations of a JIM will not have all the elements outlined below.

The JIM input/update interface is the primary communications interface between the operator and the information gathering and distribution system and, the models used within JIM. The interface should ideally handle operational data (e.g. message type, vulnerability requirements, station locations), and specialist environmental data (e.g. from sounders, or other modelling systems such as EEMS [*Moore and Lewis, 1994*]). The information flow should be hi-directional since data passed to the models may be ephemeral. Ideally, the interface should be designed for the inexperienced operator but it should be flexible enough to enable an 'expert' operator to interrogate the system in depth and, if necessary, update the model parameters manually.

The ionospheric model characterises the environment through which HF signals propagate. Typical specialist parameters required by the models may be electron density profiles at control-points, sunspot number etc. The ionospheric model is used by the propagation prediction model to determine the ray-paths and signal propagation modes (e.g. lE, 1F). The typical outputs of the propagation model are signal coverage dimensions, received signal power, MUFs, etc. These predicted propagation parameters can then be used by the communications model to predict the communications characteristics of the received signals. Typical input parameters to this communications model may be signal-to-noise ratio and antenna polar diagrams. The predicted communications system parameters can then be passed to the vulnerability assessment model for evaluation.

The assessment model compares the predicted vulnerability of the operator defined system configuration with the vulnerability requirements defined earlier. The operator defined configuration may not provide the communications resilience requested and, consequently alternative system configurations (e.g. additional frequencies) and options (different receive stations and different transmission times) should also be assessed.

The assessment model may predict more than one HF system configuration that satisfies the users' requirements. The system recommendations model uses the results of the vulnerability assessment model, and other relevant data from other systems (e.g. EEMS *[Moore and Lewis, 1994])* and, ideally, recommendations from other communications decision-aid systems (e.g. satellite, meteor burst) to first rank the configurations and then recommend the optimum EPM and ECM configuration. The recommended configurations are then output via the communications equipment interface.

Decision-aid prediction accuracy

The accuracy of the recommendations produced by any decision-aid are directly related to the data and models used. The models associated with greatest error at HF are the ionospheric model, and the propagation prediction model. The ionospheric model used in conventional HF prediction programs, e.g. REC533A [*CCIR*, 1994], IONCAP [*Teters et al.*, 1983], all use the CCIR or URSI map coefficients such as foF2, foE, hmF2, at anchor points to synthesise a median-model ionospheric profile. These simplified models, unfortunately, result in qualitatively low prediction accuracies and signal range errors of, typically, -200km. Limited improvements to these median models, however, may be obtained using sunspot updating techniques [*Uffleman et. al., 1982, Shukla and Cannon, 1994,]*. Updating is performed by comparing measured path parameters, e.g. MUF using a sounder, with a predicted path parameters using a model such as REC533A [*CCIR*, 1994]. The difference between a measured and predicted parameter such as MUF is then minimised using the ionospheric model's driving parameter (e.g. sunspot number). The new sunspot number derived is then used to make a prediction until a new measured parameter becomes available. The advantage of this 'pseudo-sunspot number' technique is its simplicity. The technique, however, has limited applicability; for example the measured path must be close to the wanted communications path. Significant ionospheric model improvements maybe obtained using near real-time data to synthesise a real-time ionosphere e.g. PRISM (Parameterised Real-time Ionospheric Specification Model, [*Daniell et al*, 1994]).

HF propagation prediction models use one of three propagation techniques: mirror reflection, analytic ray-tracing, or numerical ray-tracing. Conventional HF prediction programs (e.g. REC533A [*CCIR*, 1994]) use the mirror reflection technique for computational speed. The range and signal power accuracies, however, are low using this simple method. Superior accuracy can be achieved by analytic [*Platt and Cannon, 1994]* or numerical ray-tracing [*Jones and Stephenson, 1975]* with the former being less computationally intensive but typically less accurate. A novel analytical technique, however, is described by *Norman and Cannon, [1996]* which runs an order of magnitude faster than numerical approaches but with errors less than 2% of the numerical technique.

The DRA developed decision aid

In Version 1.0 of the decision-aid developed at DRA, the jamming and interception model (Figure 1) and the input/update interface are the major aspects. The information gathering and distribution system, and the communications interface are represented by the host 486-PC. In this early version of the decision-aid a modified version of the REC533A [CCIR, 1994] prediction program performs the functions of the ionospheric model, propagation prediction model, and the communications prediction model.

The input/update interface in Version 1.0 is a windows environment screen and has two modes of operation, one for the inexperienced HF 'operator', and the second for the experienced 'expert'. The interface developed ensures that the number of inputs required by the inexperienced 'operator' are kept to an absolute minimum. The 'operator' is denied access to required signal-to-noise ratio, required availability, operating frequencies, receiver bandwidth etc., since these only give rise to confusion and complicated input screens. These detailed parameters are input independently by the 'expert', or loaded from data files (e.g. sunspot number file, frequency plan file) prior to the decision aid being deployed with the operator.

The vulnerability assessment model in Version 1.0 is limited. Assessments are currently performed based on signal coverage within user specified areas, using the system configurations (e.g. frequencies, power) input by the expert operator. In Version 1.0 it is assumed that all receivers have equivalent systems and technologies (e.g. identical modems). This assumption, along with the use of an isotropic antenna, results in the modelling of worst case interception scenarios.

For completeness, Version 1.0 also contains a simple ground-wave propagation model for Line of Sight (LOS < 200 km) systems. This element is currently only used to display contours of signal strength and is not used in the decision making process within the vulnerability assessment model, and the systems recommendations model. The ground-wave propagation characteristics are calculated by a modified version of GRWAVE [*CCIR,* 1994] which computes the field strength of the ground wave signal on a smooth curved homogeneous earth. In this model the refractive index of the troposphere is assumed to decrease exponentially with height and the conductivity and dielectric constants, defined at the transmitter location (based on CCIR parameters), are assumed to be constant up to a range of 400 km and constant in azimuth.

The recommendations model (Figure 1) proposes system configurations based on: signal coverage predictions, and frequency range predictions. The utility of the decision-aid is described in detail by *Moore and Shukla [1995],* however, the typical outputs are summarised below.

Decision aid outputs

The decision aid displays data in two output formats. The first format is a colour sky and ground wave signal-coverage map (e.g. Figure 2) indicating station locations. The signal coverage maps, for a monthly median day, enable operators to visually inspect signal coverage consequences of potential communications link configurations and evaluate the potential effectiveness of broadcast transmission. The decision-aid currently displays the sky and ground wave signal coverage from one of ten frequencies for one time, in terms of signal-to-noise ratio (SNR) and received signal power (dBμV/m). Basic statistics of the skywave signal coverage within a 5“ box centred on each hostile receiver can also be requested by the operator. Figure 2 illustrates the utility of the tactical propagation technique. At 26 MHz the signal coverage map shows that two of the friendly stations are predicted to receive signals and two hostiles and one friendly are predicted to be in the IF and 2F propagation skip zone.

The second output format are colour frequency prediction graphs similar to those produced by PROPHET *[Argo and Rothmuller, 1979]* and facilitate point-to-point vulnerability predictions. The first graphical output shows the operational Maximum Usable Frequency (i.e. the basic MUF considering ionospheric parameters, and a correction factor to allow for propagation mechanisms above the basic MUF [*CCIR,* 1994]) over a 24 hour period. Figure 3 shows the operational MUF between one transmitter and a friendly receiver (Tx-Atlantc1), and between the transmitter and three hostile receivers (Atlantc4, 5, 6). Version 1.0 allows the maximum of 10 friendly and 10 hostile receiver locations to be analysed. The vertical lines indicate frequency ranges that are predicted *not* to propagate to the hostile receivers with the “ number of lines reflecting the number of hostiles not receiving signals. For example, in Figure 3 at 17 UT, the frequency range 17-19.5 MHz is not received by one hostile. The frequency range 19.5-22.5 MHz is not received by two hostiles and the frequency range 22.5-24.5 MHz is not received by three hostiles. For completeness, the Lowest Usable Frequency (LUF) from the friendly transmitter to the friendly receiver is also plotted.

If more than one friendly receiver station is available for communications, a composite operational MUF, i.e. the greatest hourly operational MUF, between the transmitter and any friendly is plotted and an algorithm determines the optimum friendly receiver that should be used to minimise interception. Figure 4 is a (colour) composite operational MUF output assuming three friendly and three hostile stations. Again the vertical lines indicate frequency ranges that ***cannot*** be intercepted, and the number of vertical lines reflect the number of hostiles ***not*** intercepting the signal. The colour of the horizontal bar at 35 MHz denotes the most secure friendly station. In the illustrative example, Figure 4, Friend F2 should be used between 00-04 UT, Friend F1 between 04-08 UT, F3 between 10-12 UT and F1 between 13-24 UT. No recommendation is made at 09 and 12 UT since all three hostiles are predicted to intercept the signal.

The two MUF graphs described above are only displayed to the HF 'expert'. The 'operator' receives the MUF data as a 24 hour, colour coded, frequency management table (Figure 5). The table recommends frequency ranges and the optimum friendly receiver stations that should be used to minimise interception. Hostiles predicted to intercept signals are indicated by an asterisk, and the hostile ordering, from left to right, indicates decreasing probability of interception. If all hostiles intercept the signal, then the frequencies recommended are coloured red (e.g. 09 and 12 UT) indicating that all propagating frequencies are intercepted. Under these conditions signal transmission should be avoided whenever possible. If this is not possible the red frequency range displayed is the best available to minimise signal coverage. The yellow coloured frequencies (e.g. 3-8 UT) are those that should be used with caution because at least one hostile can intercept the signal. The green frequencies (e.g. 16-23 UT) are those predicted to be safe from signal interception.

Future development of the HF decision-aid

The signal coverage predictions calculated by the jamming and interception element of the decision aid are currently based on REC533 [*CCIR,* 1994] predictions which uses a median ionospheric model and basic mirror reflection ray-tracing technique. Although improvements to the median ionospheric model will be achieved using updating techniques, is anticipated that in future versions of the decision aid (Figure 6) an improved ionospheric specification model such as PRISM [*Daniell et al,* 1994] maybe used. The potential improvements to skywave jamming and interception model are outlined in Figure 6.

A more accurate propagation prediction model using ray-tracing techniques such as the analytic ray-tracing model [*Norman and Cannon,* 1996] or the computationally intensive numerical ray-tracing technique [Jones *and Stephenson, 1975]* must also be incorporated. Within the propagation model the decision aid currently assumes isotropic antennas for worst case interception scenarios. More realistic antenna models may also be incorporated to enable more realistic system scenarios to be examined.

The vulnerability assessment model currently examines signal coverage and the path MUFs. In a future version of the model the lowest usable frequency (LUF) will also be considered to minimise signal coverage [*CCIR,* 1993]. At low frequencies, close to the LUF, skywave signals are attenuated but near vertical incidence coverage can be maintained as can ground wave coverage. Consequently, secure communications can be established within a small area. This is illustrated in Figure 7. The signal coverage at 3 MHz is restricted to the Northern Atlantic region and is intercepted by the three nearby friendlies and denied to the three distant hostiles.

In Version 1.0 the GRWAVE [*CCIR,*1994] ground wave prediction program has been incorporated for completeness but is currently not used within the assessment model. The ground conductivities used within the current decision aid are assumed to be constant in azimuth for all ranges, and land-sea boundaries are not considered. It is anticipated that in future version of the decision-aid these deficiencies will be corrected to enable a more complete HF vulnerability assessment to be made. The vulnerability model may also include hostile equipment characteristics such as signal processing time, antenna tuning time etc. These parameters will enable the effectiveness of hostiles to be evaluated more accurately within the assessment model.

The enhancements outlined above will be incorporated within the decision-aid with commensurate improvements to the users input/update interface ensuring easy use for the inexperienced 'operator'. For example, if only crude predictions are required then the operator may select the mirror reflection technique and the median ionospheric model for computational ease and speed. If, however, very accurate predictions are required in a specific area then the improved ionospheric model (e.g. PRISM *Daniell et al., [1994])* maybe selected in conjunction with analytic or numerical ray-tracing .

Conclusion

This paper has outlined a somewhat idealised design of a HF decision-aid to minimise communications vulnerability. The aid is based on the tactical use of signal propagation and exploits knowledge of the ionosphere and ray tracing techniques to minimise signal coverage and deny, or minimise, the enemies access to the radiated electromagnetic energy. The EPM improvements obtained may be used in isolation or to complement other sophisticated systems techniques such as antenna nulling and spread spectrum system.

A decision-aid system currently being developed at the DRA, for the inexperienced and expert HF communicator, has been described. This system currently uses simple frequency management techniques to minimise communications vulnerability. The decision-aid, however, suffers from an inaccurate ionospheric and propagation prediction model, but new more accurate analytic ray-tracing, and ionospheric specification models are currently being developed.

The tactical decision-aid described may be used by conventional HF operators in near real-time, as a component of other electromagnetic modelling systems (e.g. EEMS *[Moore and Lewis, 1994])* or off-line during the mission planning stage, to predict and configure the least vulnerable HF communications links. The system could also be used to automatically configure current HF equipment. This latter approach will be particularly powerful when used in conjunction with ARCS *[Arthur and Maundrell 1994]* based systems. Although this paper has concentrated on the application of the decision-aid to maximising EPM characteristics, the system may also be used to optimise communications link quality and reliability and contribute to the effective deployment of ECM systems, or even just as a HF communications training aid.

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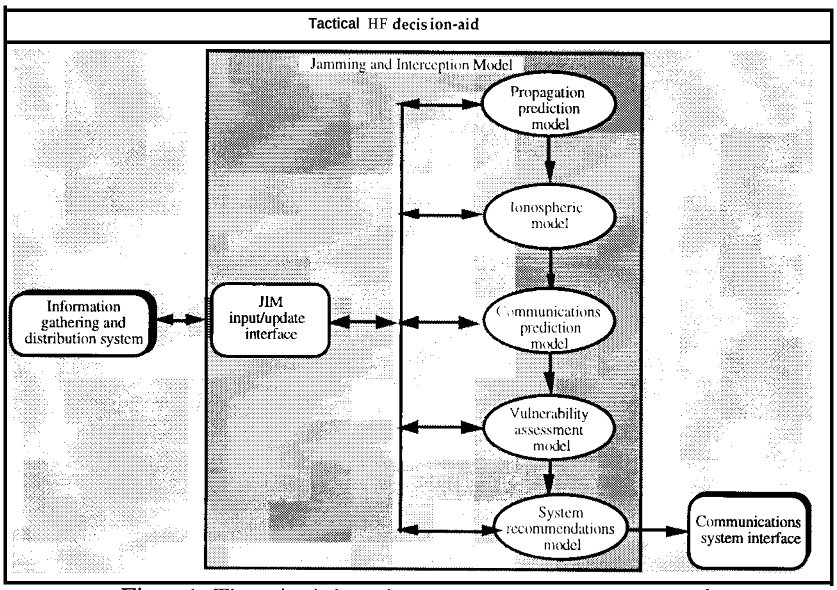


Figure 1. The principle elements of the HF-decision aid

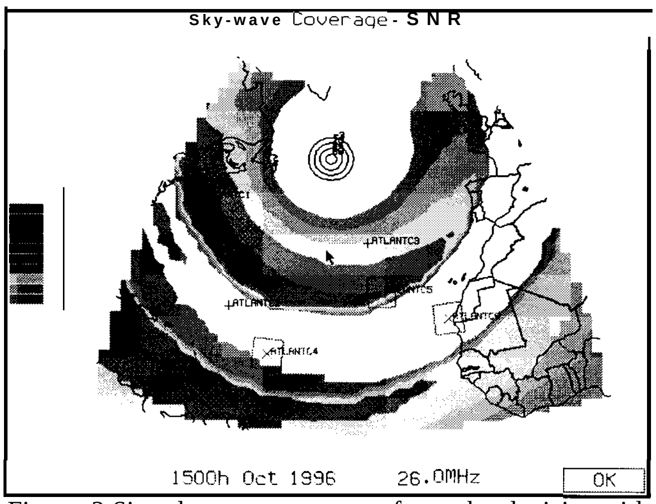


Figure 2 Signal coverage output from the decision aid showing ground and sk-ywave propagation.

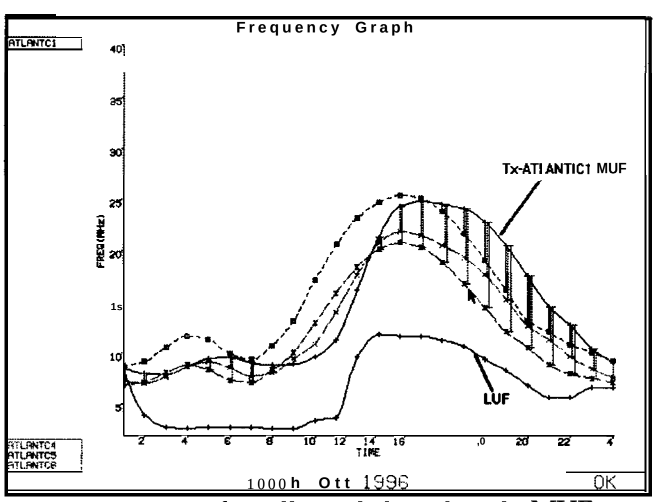


Figure 3. One friendly and three hostile MUFs.

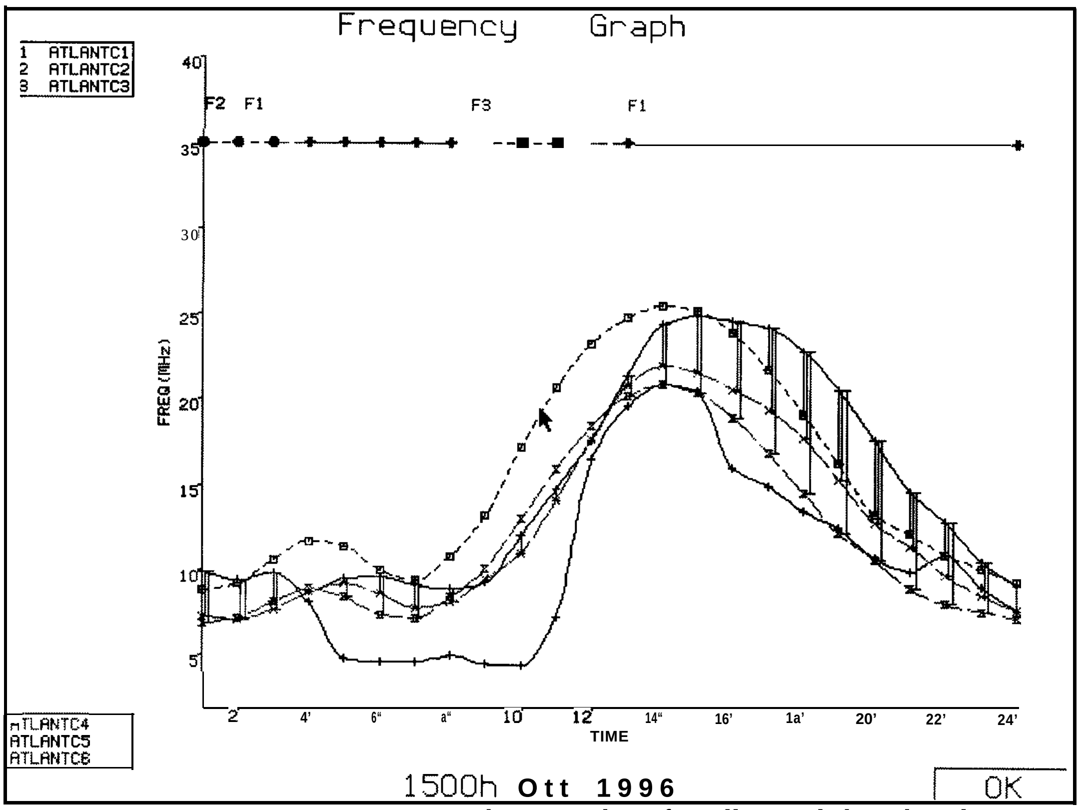
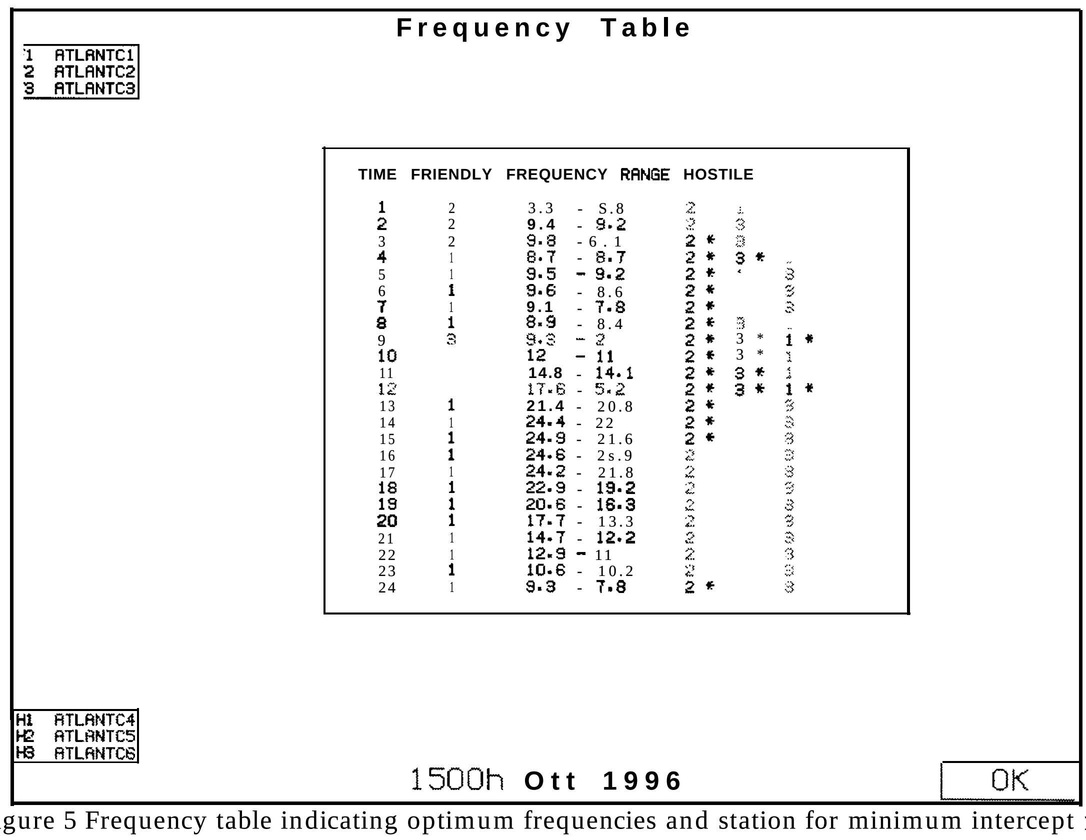


Figure 4 Composite MUF output between three friendlies and three hostiles



Frequency Table

1 ATLANTC1
2 ATLANTC2
3 ATLANTC3

TIME	FRIENDLY	FREQUENCY RANGE	HOSTILE		
1	2	3.3 - S.8	2		
2	2	9.4 - 9.2	2	3	
3	2	9.8 - 6.1	2 *	3	
4	1	8.7 - 8.7	2 *	3 *	
5	1	9.5 - 9.2	2 *		3
6	1	9.6 - 8.6	2 *		3
7	1	9.1 - 7.8	2 *		3
8	1	8.9 - 8.4	2 *	3	
9	3	9.3 - 2	2 *	3 *	1 *
10		12 - 11	2 *	3 *	1
11		14.8 - 14.1	2 *	3 *	1
12		17.6 - 5.2	2 *	3 *	1 *
13	1	21.4 - 20.8	2 *		3
14	1	24.4 - 22	2 *		3
15	1	24.9 - 21.6	2 *		3
16	1	24.6 - 2s.9	2		3
17	1	24.2 - 21.8	2		3
18	1	22.9 - 19.2	2		3
19	1	20.6 - 16.3	2		3
20	1	17.7 - 13.3	2		3
21	1	14.7 - 12.2	2		3
22	1	12.9 - 11	2		3
23	1	10.6 - 10.2	2		3
24	1	9.3 - 7.8	2 *		3

H1 ATLANTC4
H2 ATLANTC5
H3 ATLANTC6

1500h Ott 1996

OK

Figure 5 Frequency table indicating optimum frequencies and station for minimum intercept on.

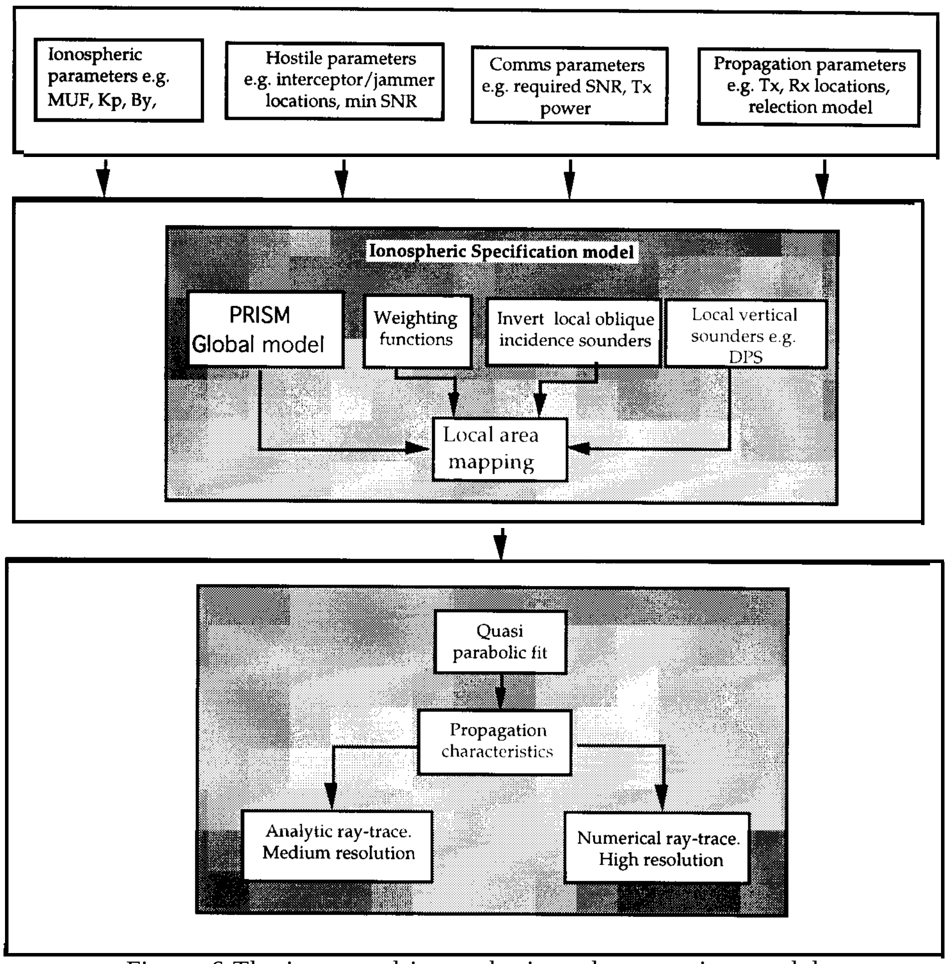


Figure 6 The improved ionospheric and ray-tracing model

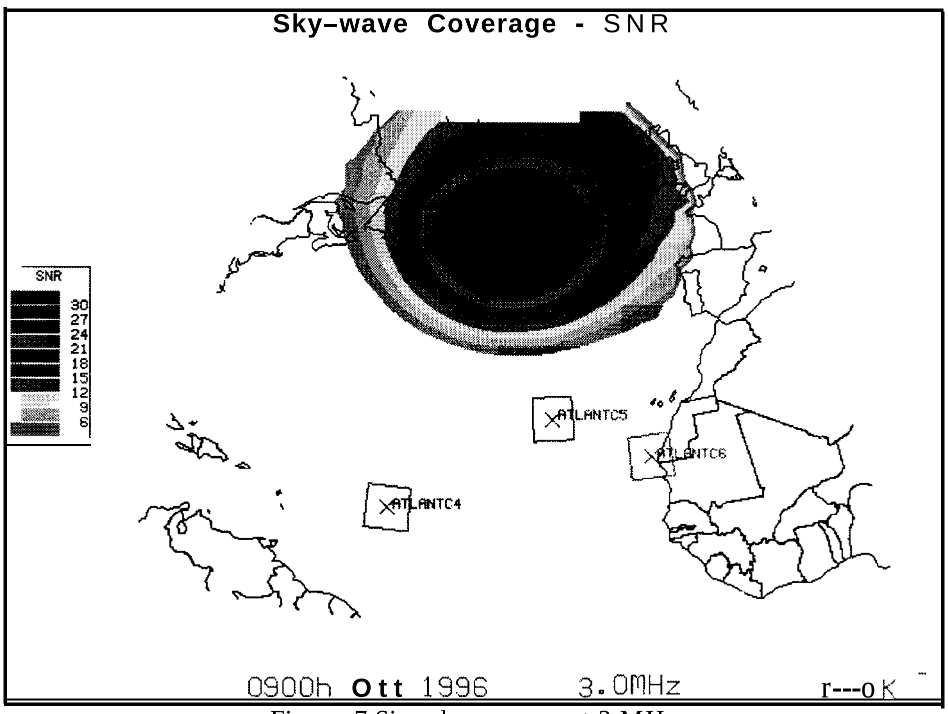


Figure 7 Signal coverage at 3 MHz